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Property-level direct and indirect deforestation for soybean production in the Amazon region of Mato Grosso, Brazil

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ABSTRACT

Brazil's Soy Moratorium solidified the world's largest traders' commitment to stop soybean purchases from production areas deforested after July 2006. The aim was to remove deforestation from the soybean supply-chain and halt one of the main drivers of forest loss in the Amazon biome. In this study, we investigated changes in deforestation at the property-level for the period 2004 to 2014. The objective was to examine direct and indirect deforestation, defined as on-property displacement and cross-parcel displacement deforestation for soybean expansion in the Amazon region of Mato Grosso, the leading soy-producing state of the Brazilian Amazon. We used publicly available property and land use data to quantify deforestation associated with cropland expansion. Similar to previous studies, we found that direct deforestation for soybean expansion declined following the implementation of the Soy Moratorium. Moreover, our analysis suggest that indirect deforestation occurred already before the implementation of the Soy Moratorium, and decreased following the first period of analyses. However, slight increases of indirect deforestation in the more recent periods, combined with decreasing direct deforestations rendered indirect deforestation to be responsible for more than half of the deforestation associated with soybean expansion. While we acknowledge the overall reduction of deforestation for soybean, our results suggest, given the increasing trends of deforestation in the Brazilian Amazon since 2013, to address indirect deforestation within the Soy Moratorium. This may be achieved by zero-property-deforestation commitments and by strengthening the integration between supply-chain actors, the soybean and beef purchasing companies and the federal policies aiming to control deforestation.

1. Introduction

Following the rapid deforestation in the Brazilian Amazon of the early 2000s, forest loss has since significantly decreased. Annual rates of deforestation decreased from more than 2.7 million ha in 2004 to 0.5 million ha in 2012. Brazils federal state of Mato Grosso is one of the most active deforestation frontiers in the Amazon during the recent decades (INPE, 2018). Most deforestation was driven by cattle ranching activities and the large-scale expansion of soybean production in the early 2000s (Arvor et al., 2011b; Macedo et al., 2012). The main factors explaining the decreasing deforestation rates are commonly understood as a combination of the implementation of environmental policies, zero-deforestation supply-chain commitments, and decreasing prices for agricultural commodities (Hargrave and Kis-Katos, 2011; Assunção et al., 2015). Policies, including territorial management, increased law enforcement, and strategic allotment of rural credits were streamlined under the Action Plan to Prevent and Control Deforestation in the Legal Amazon (PPCDAm) implemented in 2004 (Assunção et al., 2015; MMA, 2016). Supply-chain commitments were initiated following increasing international attention to deforestation in the Brazilian Amazon associated with soybean production (Soy Moratorium) in 2006, and cattle ranching (MPF-TAC and G4 Agreement) in 2009 (Greenpeace, 2006,2009; Nepstad et al., 2014; Gibbs et al., 2015, 2016). Overall, these strategies are understood to have significantly contributed to a decrease of deforestation, saving approximately 7.3 million ha of Amazonian forest between 2005 and 2009 (Assunção et al., 2015). However, since 2013 deforestation rates in the Brazilian Amazon increased from about 0.5 million ha in 2012 to 0.7 million ha in 2017 (INPE, 2018). Rising global demands for agricultural commodities may fuel additional deforestation, stressing the need to better understand

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current and past deforestation processes (Richards et al., 2012; Garrett et al., 2013; Gasparri and Le Polain de Waroux, 2015; Oliveira and Schneider, 2016).

The Soy Moratorium was the first voluntary zero-deforestation supply-chain commitment implemented in the tropics (Gibbs et al., 2015). It defines the agreement of Brazil's major soybean trading companies not to purchase soybeans produced on areas deforested after June 2006, which was changed to 2008 during the renewal of the Moratorium in 2014 (Gibbs et al., 2015). The Moratorium attracted attention within the research community, on the one hand because as a corporate social responsibility strategy it introduced new actors into conservation policy (Lambin et al., 2018), and on the other hand because it has often been evaluated to be effective in reducing deforestation for soybeans, which makes it a potential blueprint to be transferred to other commodities (Rudorff et al., 2011, 2012; Gibbs et al., 2015; Imaflora, 2016; Costa et al., 2017; Kastens et al., 2017; Silva and Lima, 2018). The commitment was drafted and monitored by the Soy Moratorium Working Group (GTS), a cooperation between industry representatives and high-profile environmental groups (Grupo de Trabalho da Soja (GTS), 2012; Gibbs et al., 2015). With its implementation, a monitoring and reporting system was set up starting for the cropping year 2007/2008 for those municipalities, whose estimated soybean area exceeds 5000 ha (Grupo de Trabalho da Soja (GTS), 2012). Land use on deforestation polygons larger than 25 ha were identified using satellite imagery acquired from the moderate resolution image spectrometer (MODIS) (spatial resolution 250 × 250 m) (Grupo de Trabalho da Soja (GTS), 2016a; Imaflora, 2016) and if croplands were found on post-deforestation land, these polygons were further investigated with high resolution satellite imagery and surveyed by air (Grupo de Trabalho da Soja (GTS), 2012; Gibbs et al., 2015; Imaflora, 2016). In case the identified polygons were used for soybean production the associated properties were added to a blacklist managed by the GTS and excluded from soybean purchases by the committed trading companies (Gibbs et al., 2015).

After the commitment, direct deforestation for soybean production decreased (Rudorff et al., 2011; Macedo et al., 2012; Rudorff et al., 2012; Imaflora, 2016; Kastens et al., 2017), and total deforestation continued to decline until 2012 (INPE, 2018). Despite these measures Mato Grosso has become the leading soybean producing state, rendering Brazil the second-leading country for soybean production worldwide (FAO, 2017; IBGE, 2017). Concerns about the effectiveness of the strategies on curbing deforestation, and interest in better understanding the dynamics of deforestation and soybean expansion in the Amazon grew with the increasing rates of deforestation since 2013 (Rausch and Gibbs, 2016; Kastens et al., 2017; Silva and Lima, 2018). For example, while the GTS monitoring program did not find a single property non-compliant with the Soy Moratorium in 2007/2008 (Grupo de Trabalho da Soja (GTS), 2009) this number increased steadily in the subsequent years to 36,000 ha in 2016/2017 (Figure SI 1), but so far direct deforestation only contributes a small fraction on overall deforestation in Mato Grosso (Grupo de Trabalho da Soja (GTS), 2017).

The discussion and concerns about the effectiveness of the Soy Moratorium addressed potential loopholes in the supply-chain commitment: the potential of leakage to different regions, how non-compliant soybean production might still enter the supply-chain, and how illegal deforestation on soybean producing properties does not necessarily lead to exclusion from commercialization.

The spatial limitation of the Soy Moratorium confined to the Amazon biome, led to the hypothesis of cross-biome leakage. Leakage describes the displacement of the environmental impact of land uses in response to the implementation of environmental policies (Meyfroidt et al., 2013). The hypothesis suggest that following the implementation of the Soy Moratorium, soybean expansion and deforestation were displaced to the Cerrado biome causing an accelerated conversion of native savannah vegetation. Although Macedo et al. (2012) rejected the hypothesis that soybean leakage was driving deforestation in the Cerrado, recent analysis identified a shift of the cropland expansion frontier moving eastwards towards the northern Cerrado region since 2008 where an increasing fraction of croplands are sourced from native vegetation (Noojipady et al., 2017). On average, one quarter of the expansion in the Cerrado occurred at the expense of native savanna vegetation, which partially offsets the averted carbon emissions from reduced deforestation in the Amazon (Noojipady et al., 2017).

Also within the Amazon biome, non-compliant soybean production was potentially able to enter the supply-chain. Gibbs et al. (2015) and Rausch and Gibbs (2016) identified two possible loopholes. First, farmers often own or rent multiple properties, but upon sale, the total harvest could be sold under the registration of those properties listed as deforestation free, while production on the other properties may not be free from deforestation (Gibbs et al., 2015; Rausch and Gibbs, 2016). Second, if soybean farmers engage in illegal deforestation under federal legislation, they are officially prohibited from commercialization of their production (Lei de Crimes Ambientais, 1998; Código Florestal, 2012). However, inconsistencies between the embargoed list under federal legislation and the property cadaster used for the Soy Moratorium, and limited monitoring and enforcement capabilities of the Brazilian environmental protection agency (IBAMA), often allowed soybeans produced on these properties to enter the supply-chain (Gibbs et al., 2015).

Indirect deforestation for soybean might have occurred at farm-level in form of a displacement of deforestation between commodities, namely between soybean and cattle production (Rausch and Gibbs, 2016). A farmer aiming to expand and secure profits from soybean production might expand its soybean area converting pastures to soybean plantation and, at the same time deforest for pasture, to keep the pasture area to support his cattle herd. This land use trajectory suggests that the underlying motivation for deforestation is the expansion of soybean cultivation. If indirect deforestation occurred in response to the implementation of the Soy Moratorium at property-level, we would term this deforestation leakage. Moreover, pastures and sometimes rice plantation play an important role for the preparation of soil for subsequent soybean production (Grupo de Trabalho da Soja (GTS), 2009; Macedo et al., 2012). Deforestation for these land uses might additionally occur in anticipation for amnesty of past deforestation in future renewals of the Moratorium, similar to the amnesty granted for deforestation between 2006 and 2008 agreed on during the renewal in 2014 (Silva and Lima, 2018).

Analyzing and quantifying direct and indirect deforestation for soybean expansion will potentially increase the understanding of deforestation processes in the Brazilian Amazon and may help to inform subsequent policy initiatives to curb further deforestation. In this paper we explicitly addressed indirect deforestation for soybean at property-level. In detail, we analyzed the area of direct conversions from forests to soybean fields, indirect deforestation for soybean expansion measured as the amount of soybean expanding into pastures in combination with deforestation for cattle ranching occurring on the same property and or in its direct neighborhood. The specific research questions were:

How much direct and indirect deforestation for soybean production at property-level occurred in the Amazon biome of Mato Grosso between 2004 and 2014?

Did on-property indirect deforestation increase following the implementation of the Soy Moratorium in the Amazon biome of Mato Grosso?

2. Methods

2.1. Study region

This study focusses on the Amazon biome within the federal state of Mato Grosso (Fig. 1). Extensive cattle ranching with low stocking

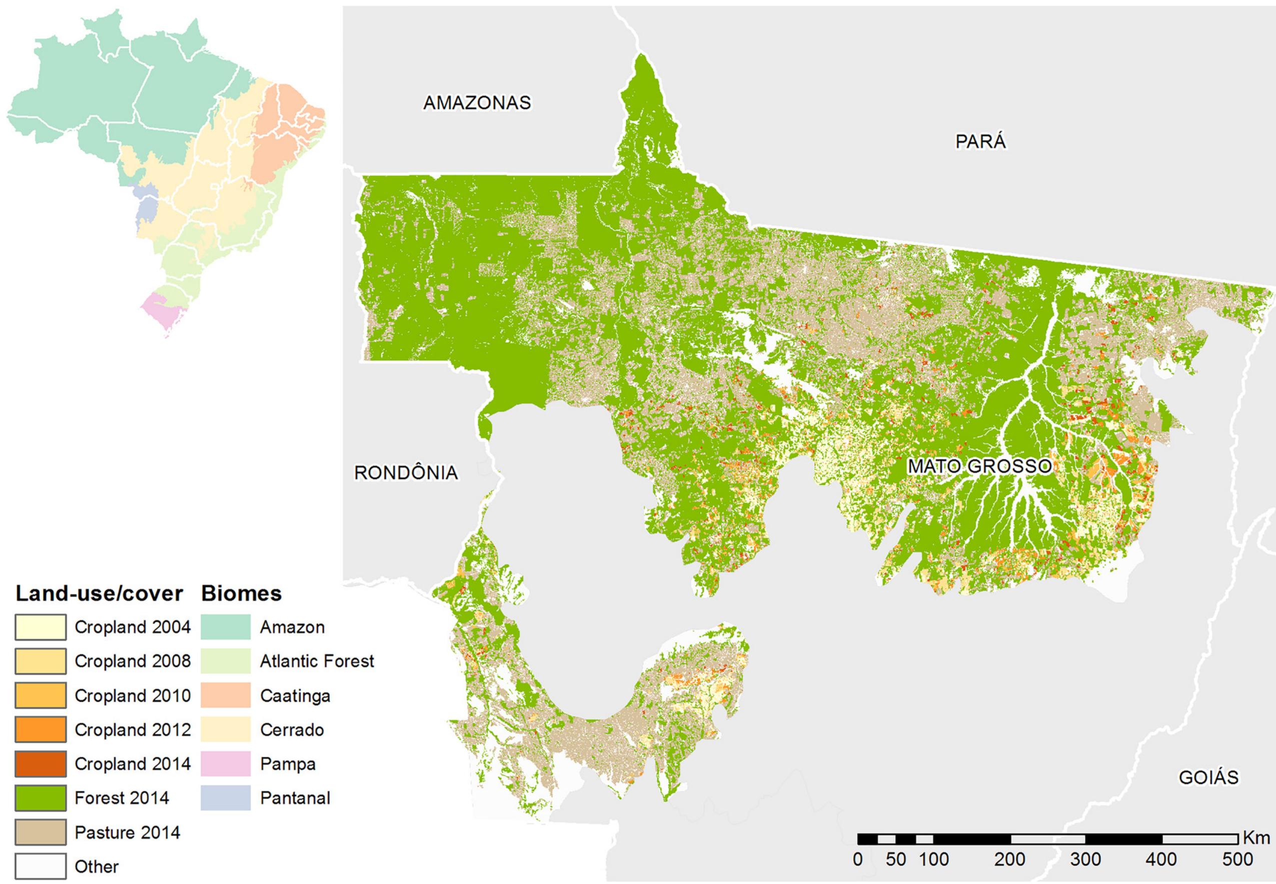

Fig. 1. Cropland expansion (2004–2014) and land use and cover types (2014) in the Amazon biome of Mato Grosso (Source: INPE, 2015; MMA, 2015).

densities was the predominant land use before large-scale agriculture expanded into the region (Hecht, 1993; Nepstad et al., 2006). Advances in the adaptation of soybean varieties during the 1990s overcame previous constraints on tropical soy production related to the acidic, aluminum-rich soils and short photoperiods in the Amazon (Spehar, 1995; Fearnside, 2001; Spera et al., 2014). In the Amazon biome of Mato Grosso, cropland for soybean production more than doubled from 0.88 million ha in 2001 to 1.96 million ha in 2007, comprising 94.8% and 97.3% of total cropland, respectively (Arvor et al., 2011b). Along with this expansion, the adoption of double cropping systems with soybean as the first crop, followed by maize or cotton increased the total annual agricultural productivity (Arvor et al., 2011a; Macedo et al., 2012; Spera et al., 2014). While the cropland area throughout Mato Grosso state increased by 75% from 3.3 million ha in 2001 to 5.8 million ha in 2011, the area of double-cropped land increased roughly six times, from 0.5 million ha to 2.9 million ha, of which 92% was soybean-maize rotation (Spera et al., 2014). Particularly in the Amazon biome of Mato Grosso soybean production occurred on 94.8% (2001) and 97.3% (2007) of all cropland (Arvor et al., 2011b). Soybeans pervasive dominance on crop fields make this commodity the principal force underlying cropland expansion in the study region. Between 2001 and 2005, 26% of new croplands were sourced from primary forests, causing direct deforestation, and 74% were converted from pastures (Macedo et al., 2012). Following the Soy Moratorium, large scale deforestation (> 25 ha plots) for cropland expansion fell to 1% in 2009 (Macedo et al., 2012).

2.2. Data and pre-processing

We used the TerraClass land use and cover product provided by the National Institute for Space Research (INPE), covering the Brazilian Amazon biome for the years 2004, 2008, 2010, 2012 and 2014 (INPE, 2015). The TerraClass maps provide post-deforestation land uses based on the annual gross forest loss maps made available by the Brazilian Deforestation Monitoring Program (PRODES) (INPE, 2018). The land use classification procedure aimed for consistency between years and class semantics, to facilitate an analysis of land use trajectories (INPE, 2015; Almeida et al., 2016). It combines the PRODES deforestation maps and time series information for mapping cropped areas from the Moderate Resolution Imaging Spectroradiometer (MODIS) at a 6.25 ha resolution (Almeida et al., 2016). The land use categories relevant to our analysis include croplands (*agricultura annual*), used as surrogate for soybean cultivation, four pasture categories referring to different vegetation covers (*pasto com solo exposto, pasto limpo, pasto sujo, and regeneração com pasto*), which were merged to one pasture class, forest (*floresta*), and deforestation (*desflorestamento*) that occurred within the year of classification (no post deforestation land use was assigned yet). The overall accuracy of TerraClass 2008 was estimated to be 89.7% for the entire Amazon biome (when pasture classes are merged; Almeida et al., 2016). Because of the minimum mapping unit of 6.25 ha, we selected 6.25 ha as a minimum conversion threshold throughout our analyses. We defined deforestation for cropland or pasture as the conversion from the class *forest* or *deforestation* to *cropland*, or *pasture* respectively, mapped between a sequential pair of land use datasets. We reported deforestation quantities as the mean annual conversion rate in ha throughout the analysis.

We obtained private rural property data from the *Cadastro Ambiental Rural* (CAR, 2018) public database, an instrument created under the revised Brazilian Forest Code intended to enforce and monitor law compliance and promote natural resources conservation (Código Florestal, 2012; SICAR, 2017). Rural landholders are required to submit georeferenced property boundaries to the CAR registry system prior to

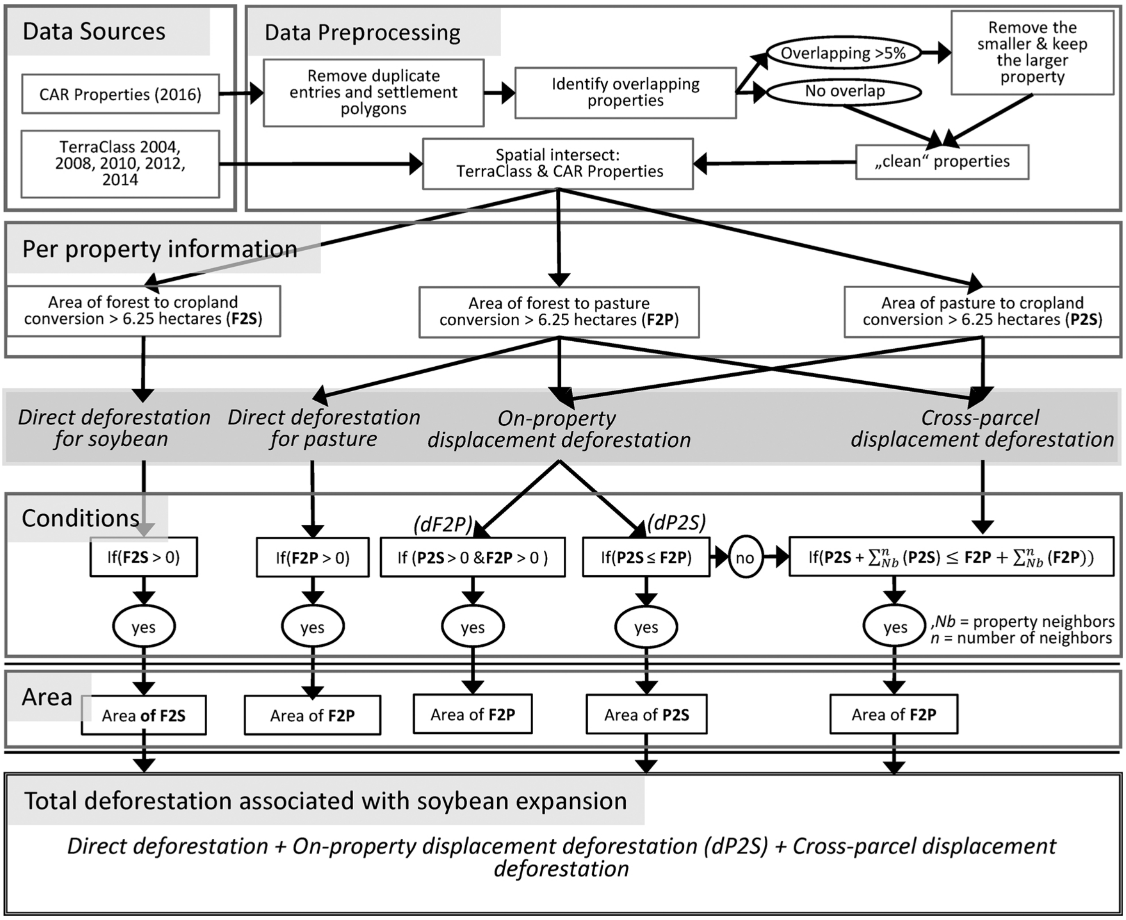

Fig. 2. Workflow identifying and quantifying direct deforestation, on-property displacement, and cross-parcel displacement deforestation related to soybean expansion. F2S: Forest to soybean conversion; F2P Forest to pasture conversion: P2S Pasture to soybean conversion.

January 1st 2019, as a condition for accessing credit (Ministério da Fazenda/Banco Central do Brasil, 2018). Property boundaries are declared by landowners, and at this stage may contain conflicting or false information. Prior to our analysis we identified and modified or removed spatially inconsistent or geometrically erroneous properties in the CAR dataset (Fig. 2). The final dataset comprised 48,282 properties covering an area of 25.2 million ha, 52% of the Amazon biome of Mato Grosso. The CAR and TerraClass land use and cover datasets were reprojected and aligned to the Albers Equal Conic (ESRI: 102033) projection with a 30 × 30 m resolution.

2.3. Analysis

We conceptualized and calculated *direct deforestation*, *on-property displacement,* and *cross-parcel displacement* deforestation as depicted in Fig. 2. Direct deforestation for soybean (F2S) was quantified as the conversion from forest or deforested areas to cropland (Fig. 2). Similarly, direct deforestation for pasture (F2P) quantified the conversion from forest or deforested areas to pastures (Fig. 2). We conceptualized on-property displacement deforestation as the process of soybean expanding over pasture (P2S) in combination with deforestation for pasture (F2P) within the same property (Fig. 2). We provided two quantifications of displacement deforestation, one reporting all deforestation for pasture on the property displacing cattle ranching (dF2P); the other one, more restrictively, reporting the area of soybeans expanding over pastures as the displaced area caused by the conversion of pastures to soybean (dP2S). Additionally, we restricted the latter quantification to those cases where the area of deforestation for pasture (F2P) equaled or was larger compared to the area of soybean expansion over pasture (P2S).

Cross-parcel displacement deforestation described the process of displacement deforestation between neighboring properties (Fig. 2). We included the cross-parcel displacement deforestation to account for farmers which managed multiple properties (Richards and VanWey, 2015; Rausch and Gibbs, 2016). Because the property dataset did not indicate if or which farmers manage multiple properties, we analyzed land use changes between neighboring properties assuming that proximate land conversions are more likely related to each other than those between distant properties. As neighborhood we selected the adjacent parcels for each property within a maximum distance of 200 m between boundaries to account for spatial inaccuracies of the CAR data.

Cross-parcel displacement, as defined within this analysis, only relates a focal parcel to its neighbors if pastures were converted to soybean (P2S), and the loss of pasture area was regained in the neighboring properties by deforestation (F2P, Fig. 2). The quantity of cross-parcel displacement was only reported as the displaced area of pasture to soybean conversion (P2S), while any additional deforestation in the neighboring properties was assumed to be independent, or in addition to the displacement deforestation.

Overall deforestation caused by soybean expansion was calculated as the summed area of direct deforestation, on-property displacement deforestation (dP2S) and cross-parcel displacement deforestation (Fig. 2).

3. Results

Total annual deforestation rates in the Amazon biome of Mato Grosso declined from more than 1 million ha in 2004 to 0.1 million ha

Table 1
Overall deforestation and direct, on-property displacement, and cross-parcel displacement deforestation associated with soy expansion per year.

Years	Deforestation in the Amazon region of Mato Grosso	Deforestation in properties	Direct deforestation for soybean expansion in properties		Direct deforestation for pasture on soybean producing properties	On-property displacement deforestation (dF2P)	On-property displacement deforestation (dP2S)	Cross-parcel displacement deforestation	Total deforestation for soybean expansion in properties*	
	Ha	Ha	Ha (#properties)	Percent*	Ha (#properties)	Ha (#properties)	Ha (#properties)	Ha (#properties)	Ha	Percent*
2004 – 2008	435,350	245,342	55,536 (1,623)	22%	21,800 (662)	13,189 (376)	2,744 (116)	27,091 (194)	85,371	35%
2008 – 2010	96,000	29,198	4,270 (164)	14%	9,557 (229)	4,932 (99)	317 (29)	7,315 (59)	11,902	41%
2010 – 2012	93,850	32,294	2,982 (132)	9%	4,243 (121)	1,695 (48)	408 (10)	1,522 (24)	4,912	15%
2012 – 2014	110,700	42,621	1,435 (67)	3%	3,659 (113)	1,884 (51)	324 (12)	1,227 (23)	2,986	7%

* Percent of deforestation in properties.

in 2014 (INPE, 2018). About half of the deforestation from 2004 throughout 2008 occurred within the mapped property boundaries (58%), declining in the successive years (2009–2010, 33%; 2011–2012, 37%; 2013–2014, 42%; Table 1). Of these properties, 3070 (6%) were used for soy cultivation in 2004. This number roughly doubled by 2014 to 6048 properties (13%), increasing the number of properties within the analysis. Similarly, the area under cropland within these properties more than doubled during the same time from 0.86 million ha to 2.2 million ha. Located within the properties we found approximately 3 million ha (25%) of the remaining forest area in 2014 (Table SI 1.). However, many properties had little or no forest remaining within their boundaries; of the 6048 properties cultivating soy in 2014, 2092 (32%) had less than 6.25 ha of forest cover (Table SI 1).

Our results showed a distinct reduction of deforestation for soybeans measured as direct deforestation and indirect deforestation, i.e. on-property displacement deforestation and cross-parcel displacement deforestation. Direct deforestation for soybean decreased from 55,536 ha between 2004 and 2008 to 1435 ha between 2012 and 2015. The largest reduction occurred following the first period of observation, after 2008, when the Soy Moratorium was fully implemented and the monitoring system was in place. Following 2008, we found a tenfold decrease of direct deforestation for soybean production to 4270 ha between 2008 and 2010, dropping further to 1.435 ha between 2012 and 2014 (Fig. 2A, Table 1).

Direct deforestation for pasture within soy cultivating properties declined along a similar gradient (Fig. 2A). In absolute numbers deforestation for pasture declined from 21,800 ha (between 2004 and 2008) to 3659 ha (between 2012 and 2014). Overall, deforestation for pastures was already a large contributor to deforestation on soybean producing analysis throughout the analysis period (Fig. 3A). This deforestation occurred partly on properties that expanded their soybean areas at the same time over pastures. Between 2004 and 2008, 13,189 ha of deforestation for pasture occurred on properties that expanded soybean areas on pastures, as an on-property displacement (dF2P) process. This displacement deforestation declined for the following observation periods to 4932 ha and 1695 ha, before it marginally increased to 1884 ha in the most recent period of analysis (Table 1, Fig. 3D). Similarly the more restrictive measure of on-property displacement (dP2S), only referring to the conversion area of pasture to soybeans as displacement deforestation, indicated a decline of indirect deforestation from 2743 ha to 317 ha between 2008 and 2010, fluctuating around 300 and 400 ha in the following observation periods (Table 1, Fig. 3E).

Cross-parcel deforestation declined from 27,091 ha between 2004 and 2018 to 7315 ha between 2008 and 2010 and further to 1522 ha, dropping to 1227 ha between 2012 and 2014 (Table 1, Fig. 3F). Throughout the analysis cross-parcel displacement deforestation was distinctively higher compared to on-property displacement deforestation (dP2S). Moreover, the decline of deforestation was less abrupt, rather following a similar gradient to the decline of deforestation for pasture (Fig. 3F).

Overall, we found that indirect deforestation was present and even more dominant in the beginning of the analysis period between 2004 and 2008, dropped sharply for the second period of analysis between 2008 and 2010, following the implementation and monitoring of the Soy Moratorium, and subsequently indicated minor trends of increasing displacement activities (between 2010 and 2012 on-property displacement (dP2S) increased; between 2012 and 2014 on-property displacement (dF2P) increased).

Combining the measures of deforestation for soybean, direct deforestation, on-property displacement deforestation (dP2S) and cross-parcel spillover deforestation (Fig. 1) we found the biggest reduction of deforestation associated with soybean expansion between the first and second period of analysis, dropping from 85,371 ha to 11,902 ha of mean annual deforestation (Table 1, Fig. 3C). Direct deforestation for soy contributed the largest decline to the overall reduction of

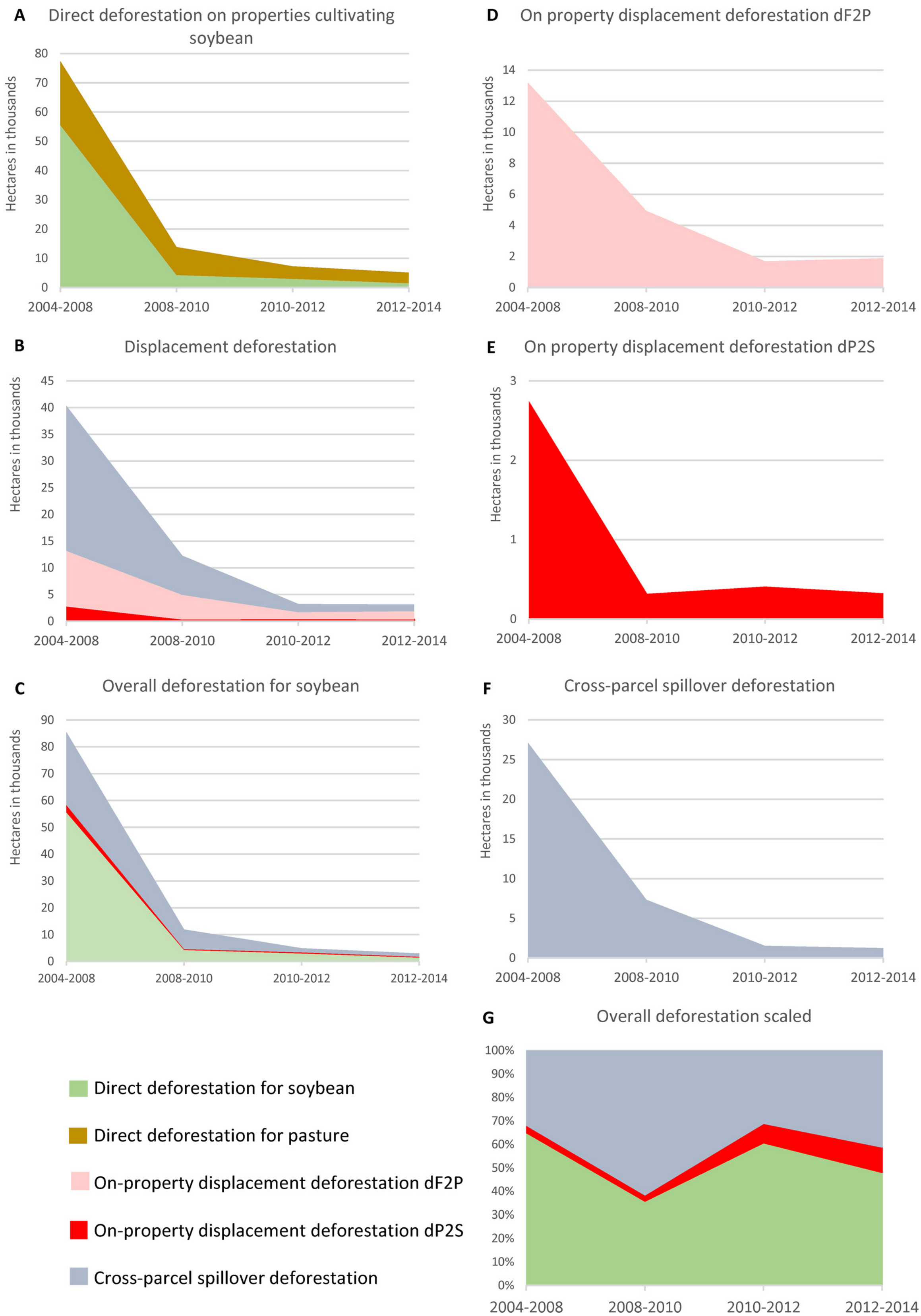

Fig. 3. Areas (in thousand hectares) and fraction of the different deforestation trajectories. The indicated years refer to the respective pairs of TerraClass land use classifications.

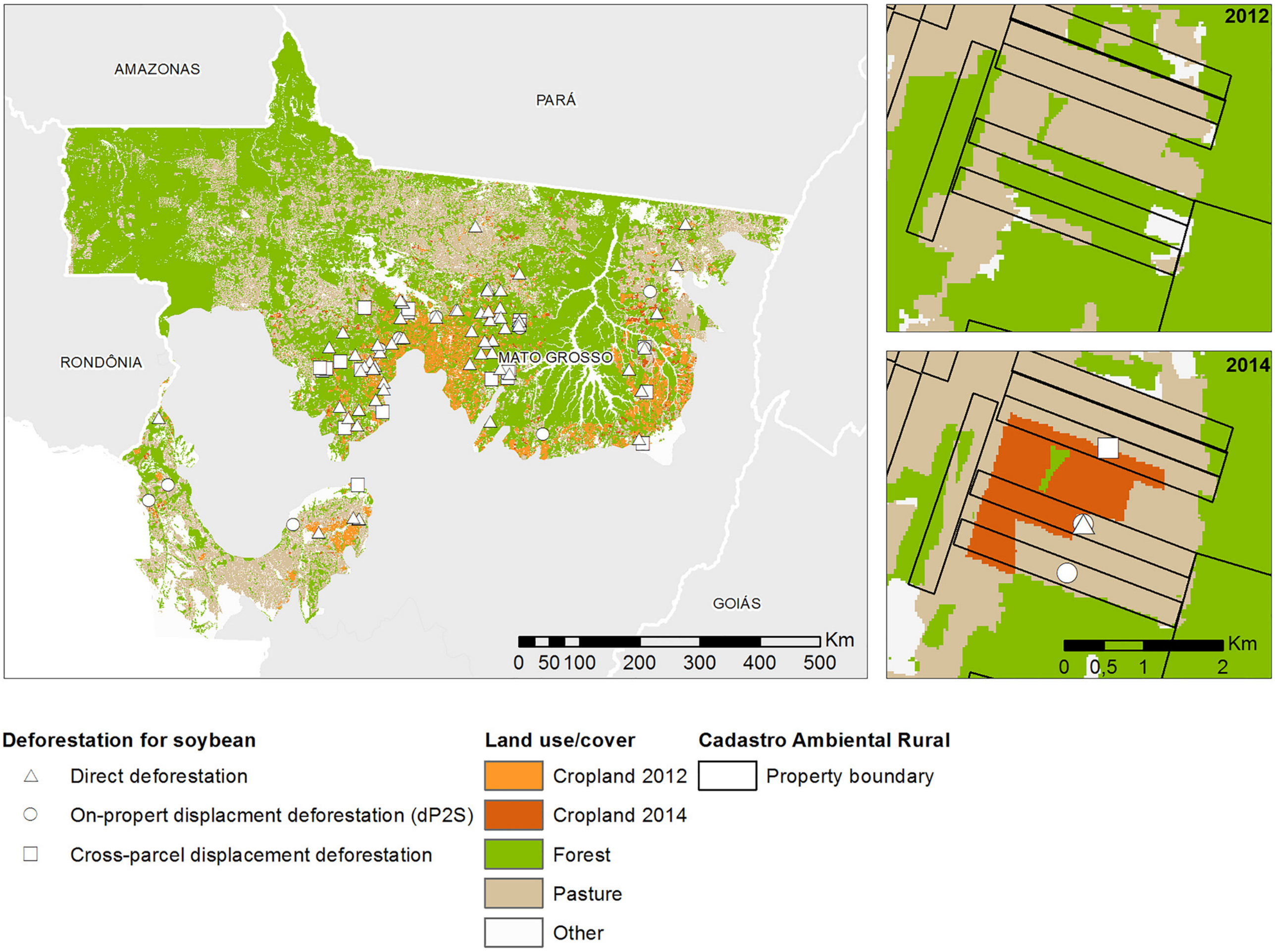

Fig. 4. Left, deforestation associated with soybean expansion (direct deforestation, on-property displacement (dP2S) deforestation, cross-parcel deforestation) between 2012 and 2014. Right, selected example of direct deforestation, on-property displacement (dP2S) deforestation, and cross-parcel displacement deforestation.

deforestation. Overall, on-property total deforestation for soybean continued to decline to 4912 ha and 2986 ha between 2010 and 2012 to 2012 and 2014, respectively. As Fig. 3G indicates a shift between the relative contributions of deforestation associated with soybean expansion occurred in the recent periods of observation. We found the fractions of indirect deforestation for soybean, on-property displacement and cross-parcel displacement, to increase from 40% between 2010 and 2012 to 52% between 2012 and 2014 (Fig. 3G). This deforestation associated with soybean expansion between 2012 and 2014 occurred at the frontiers of cropland expansion into the remaining large forest patches and partially into areas dominated by cattle ranching (Fig. 4).

4. Discussion

This is the first analysis providing estimates of direct and indirect deforestation for soybean expansion at the property-level for the Amazon biome of Mato Grosso. We approximated soybean expansion and associated deforestation, assuming that cropland areas in TerraClass correspond to planted soybean. We argued that this is legitimate, because 97% of croplands in the Amazon region of Mato Grosso were used for soy cultivation during our study period (Arvor et al., 2011b) and soy production is ascribed to be the dominant force underlying the expansion of croplands in the region (Fearnside, 2001; Arvor et al., 2011b, a; Macedo et al., 2012).

Overall our results supports earlier studies in showing that deforestation for soybean production has decreased by an impressive magnitude after the implementation of the policies aiming to reduce deforestation, including the Soy Moratorium (Rudorff et al., 2011; Hecht, 2012; Macedo et al., 2012; Rudorff et al., 2012; Arima et al., 2014; Nepstad et al., 2014; Assunção et al., 2015; Imaflora, 2016; Grupo de Trabalho da Soja (GTS), 2016b), and this not only for direct deforestation, but also the measures of indirect deforestation. Our analysis pointed out that indirect deforestation for soybean expansion at property-level occurred already before the implementation of the Soy Moratorium. Deforestation displacement was not necessarily a new strategy occurring in response to the restrictions of the Soy Moratorium but has been a constant practice of land use management. The consistency of the reduction of indirect deforestation in the subsequent periods and earlier analysis on land use change trajectories by, for example, Macedo et al. (2012) and Morton et al. (2006) support this finding. Their analysis showed that most soybean expansion occurred over pastures, while areas newly deforested were most often used as pastures. Similarly the Soy Moratorium Working Group identified most non-compliant soybean production expanding over areas, which were deforested since three or more years (Grupo de Trabalho da Soja (GTS), 2014, 2017). Our analysis adds to these findings by showing that the process of deforestation displacement from soybean to pasture use partially occurred within properties during all observation periods, where soybean expansion displaced deforestation to cattle ranching within the same properties.

The results indicate a displacement of deforestation, but do not conclusively support hypotheses of property-level deforestation leakage following the implementation of the Soy Moratorium. The reduction of direct and indirect deforestation for soybeans indicates the effectiveness of the implemented policies in reducing deforestation, most importantly the Soy Moratorium and the policies within the framework of the PPCDAm (Rudorff et al., 2011; Nepstad et al., 2014; Assunção et al., 2015; Gibbs et al., 2015, 2016). Nevertheless, the Soy Moratorium Working Group found an increasing amount of soybean plantation violating the Soy Moratorium each year, with the only exemption in 2014, when the deforestation cut-off value was shifted from 2006 to 2008, effectively amnestying deforestation for soybean occurring before 2008 (Figure SI 1)(Grupo de Trabalho da Soja (GTS), 2009,2010,2011,2012,2013,2014,2015,2016b,2017; Silva and Lima, 2018). The favorable market conditions (World Bank, 2017) and a lack of enforcement of illegal deforestation (Azevedo et al., 2015; Gibbs et al., 2015) might explain the recent increases of Soy Moratorium violations and the slight increases of on-property displacement deforestation (dF2P and dP2S).

The reduction of direct deforestation in combination with the slight increases of indirect deforestation in the most recent periods of analysis led to a shift of individual contributions to deforestation for soybean. During the most recent period of analysis indirect deforestation became the larger contributor (52% see Fig. 2) to soybean driven deforestation. This is especially relevant because most soybean expansion in violation of the Soy Moratorium expand on areas deforested multiple years before (Grupo de Trabalho da Soja (GTS), 2017), potentially referring to the processes of deforestation displacement. Analyzing long term trajectories and displacement processes beyond the 2–4 years periods taken within this analysis might uncover additional long-term displacement processes.

The largest uncertainty of our analysis may be related to the completeness and validity of the CAR dataset and our estimate of cross-parcel spillover deforestation. At date property boundaries are self-declared by the respective landowner and the completion date, institutionalizing the registry, has been delayed four times, with the latest change from December 2017 (Lei N. 13.295/, 2016) to January 2019 (Ministério da Fazenda/Banco Central do Brasil, 2018). Assuming not all properties are yet registered, we may underestimate direct and indirect on-property deforestation rates for soybean production. The lack of information of ownership or management pose an important data restriction, which makes it difficult to explore potential land management practices across different properties, owned or rented by the same farmer. Within our measure of cross-parcel spillover deforestation we might falsely label deforestation events to be related. This could have caused an overestimate of spillover deforestation. We aimed to reduce the risk of overestimation by reporting only the area of pasture to soybean conversion in the focal property, conditioned upon that the area deforested for pasture was similar or larger than the pasture area lost for soybeans. Any deforestation excessing the conversion in the focal property was assumed to be independent, or additional to the expansion of soybeans. Similarly, if deforestation for pasture was smaller than the area converted from pastures to soybean in the focal property, we did not include the deforestation in the calculation. Future analysis would significantly gain from land ownership and management information, enabling research to better understand land use changes at the farm management level.

Overall, we found that deforestation for soybean production at property-level decreased after the implementation of the Soy Moratorium, for direct and indirect measures of deforestation . In perspective of the persistency of indirect deforestation for soybean expansion we suggest that future efforts to decrease deforestation will need to acknowledge the interaction of land use changes between soybean expansion over pastures and deforestation for cattle ranching at farm-level. In detail, we suggest that on-property displacement deforestation could be targeted within the Soy Moratorium by expanding the monitoring to property-level deforestation incidents, incorporating displacement processes or effectively implementing a zero-property-deforestation commitment, and by strengthening the enforcement and integration of federal environmental laws, such as the Brazilian Forest Code within the Soy Moratorium (Azevedo et al., 2015). Effective implementation and monitoring of the G-4 Cattle Agreement might additionally contribute to reduce deforestation indirectly linked to soybean expansion.

5. Conclusion

Since 2006 the Soy Moratorium has sought to ban deforestation from the soybean supply-chain. This analysis provided the first integrated results of soybean-related deforestation including direct and indirect deforestation at the property-level. We corroborate findings from earlier analyses indicating that direct deforestation for soybean expansion decreased, and we contribute new data on indirectly associated deforestation for soybean expansion. Collectively, our findings support the success of the Soy Moratorium in decreasing direct deforestation for soybean expansion. While indirect deforestation driven by soybean expansion decreased during the same period, its relative importance within total deforestation for soybean increased. In the most recent period of analysis, indirect deforestation made more than half of the total deforestation for soybean. Based on our results, we stress that if the Soy Moratorium aims to ban all deforestation from the soybean supply-chain, future agreements will need to integrate the interactions between the different agricultural commodities to account for indirect deforestation processes. Key aspects of future policy strategies to curb deforestation related to soybean expansion in the Brazilian Amazon may include a zero-deforestation commitment applicable to the entire property, and a better integration between the supply-chain actors, the soybean and beef purchasing companies, and the federal institutions responsible for the implementation and enforcement of the policies aiming to control deforestation.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.landusepol.2018.07.010.

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